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Observational consequences of the Partially Screened Gap

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Abstract. Observations of the thermal X-ray emission from old radio pulsars implicate that the size of hot spots is much smaller than the size of the polar cap that follows from the purely dipolar geometry of pulsar magnetic field. Plausible explanation of this phenomena is an assumption that the magnetic field at the stellar surface differs essentially from the purely dipolar field. Using the conservation of the magnetic flux through the area bounded by open magnetic field lines we can estimate the surface magnetic field as of the order of $10^{14}G$. Based on observations that the hot spot temperature is about a few million Kelvins the Partially Screened Gap (PSG) model was proposed which assumes that the temperature of the actual polar cap equals to the so called critical temperature. We discuss correlation between the temperature and corresponding area of the thermal X-ray emission for a number of pulsars.

We have found that depending on the conditions in a polar cap region the gap breakdown can be caused either by the Curvature Radiation (CR) or by the Inverse Compton Scattering (ICS). When the gap is dominated by ICS the density of secondary plasma with Lorentz factors $10^2 - 10^3$ is at least an order of magnitude higher than in a CR scenario. We believe that two different gap breakdown scenarios can explain the mode-changing phenomenon and in particular the pulse nulling. Measurements of the characteristic spacing between sub-pulses (P_2) and the period at which a pattern of pulses crosses the pulse window (P_3) allowed us to determine more strict conditions for avalanche pair production in the PSG.

1. Introduction

The Standard model of radio pulsars assumes that there exists the Inner Acceleration Region (IAR) above the polar cap where the electric field has a component along the opened magnetic field lines. In this region particles (electrons and positrons) are accelerated in both directions: outward and toward the stellar surface (Ruderman & Sutherland (1975)). Consequently, outflowing particles are responsible for generation of the magnetospheric emission (radio and high-frequency) while the backflowing particles heat the surface and provide required energy for the thermal emission. The Vacuum Gap model assumes that ions cannot be extracted from stellar surface due to huge surface magnetic field of a pulsar. On the other hand it predicts the surface temperature of few million Kelvins (heating by backflowing particles). As shown by Medin & Lai (2007) for such high temperatures the ions extraction from surface cannot be ignored. In fact for surface temperature few million Kelvins the gap can form only if surface magnetic field is much stronger than the dipolar component ($B_s = 10^{14}G$).

The analysis of X-ray radiation is an excellent method to get insight into the most intriguing region of the neutron star (NS). X-ray emission seems to be a quite common

feature of radio pulsars. In general X-ray radiation from an isolated NS can consist of two distinguishable components: the thermal emission and the nonthermal emission. The thermal emission can originate either from the entire surface of cooling NS or the spots around the magnetic poles on stellar surface (polar caps and adjacent areas). The nonthermal component is usually attributed to radiation produced by Synchrotron Radiation and/or Inverse Compton Scattering from charged relativistic particles accelerated in the pulsar magnetosphere. For most observations it is very difficult to distinguish contribution of different components (thermal and nonthermal). To get an information about polar cap of radio pulsars we analysed X-ray radiation from old pulsars as their surface is already cooled down and their magnetospheric radiation (nonthermal component) is also significantly weaker.

The blackbody fit allows us to obtain directly the temperature (T_s) of the hot spot. Using the distance (D) to the pulsar and the luminosity of thermal emission (L_{bol}) we can estimate the area (A_{pc}) of the hot spot. In most cases (A_{pc}) differs from the conventional polar cap area $A_{dp} \approx 6.2 \times 10^4 P^{-1} \text{ m}^2$, where P is the pulsar period. We use parameter $b = A_{dp}/A_{pc}$ to describe the difference between A_{dp} and A_{pc} . Pulsars for which it is possible to determine polar cap size (old NSs) show that the actual polar cap size is much smaller ($b \gg 1$) than the size of conventional polar cap (see Tab. 1).

The surface magnetic field can be estimated by the magnetic flux conservation law as $b = A_{dp}/A_{pc} = B_s/B_d$, where $B_d = 2.02 \times 10^{12} (P\dot{P}_{-15})^{0.5}$, and $\dot{P}_{-15} = \dot{P}/10^{-15}$ is the period derivative. The X-ray observations suggest that surface magnetic field strength at polar cap should be of the order of 10^{14} G. On the other hand we know from radio observations that magnetic field at altitudes where radio emission is generated should be dipolar. To meet both these requirements Partially Screened Gap model assumes the existence of crust-anchored local magnetic anomalies which affect magnetic field only on short distances. According to our model the actual surface temperature equals to the critical value ($T_s \sim T_{crit}$) which leads to the formation of Partially Screened Gap.

2. Partially Screened Gap

The PSG model assumes existence of heavy (Fe^{56}) ions with density near but still below corotational charge density (ρ_{GJ}), thus the actual charge density causes partial screening of the potential drop just above the polar cap. The degree of shielding can be described by shielding factor $\eta = 1 - \rho_i/\rho_{GJ}$, where ρ_i is the charge density of heavy ions in the gap. The thermal ejection of ions from surface causes partial screening of the acceleration potential drop $\Delta V = \eta \Delta V_{max}$, where ΔV_{max} is the potential drop in vacuum gap. Using calculations of Medin & Lai (2007) we can express the dependence of the critical temperature on pulsar parameters as $T_{crit} = 1.1 \times 10^6 (B_{14}^{1.1} + 0.3)$, where $B_{14} = B_s/10^{14}$, $B_s = bB_d$ is surface magnetic field (applicable only if hot spot is observed i.e. $b > 1$).

The actual potential drop ΔV should be thermostatically regulated and there should be established a quasi-equilibrium state, in which heating due to electron/positron bombardment is balanced by cooling due to thermal radiation (see Gil et al. (2003) for more details). The necessary condition for formation of this quasi-equilibrium state is

$$\sigma T_s^4 = \eta e \Delta V c n_{GJ}, \quad (1)$$

where σ is the Stefan-Boltzmann constant, e - the electron charge, $n_{GJ} = \rho_{GJ}/e = 6.93 \times 10^{12} B_{14} P^{-1}$ is the corotational number density.

Using the Gauss's law and Faraday's law of induction we can find the formula for potential drop in a gap region

$$\Delta V/h^2 + \Delta V/h_\perp^2 = 4\pi\eta B_s \cos(\alpha) / cP \quad (2)$$

where h is gap height, h_\perp is spark width and α is the inclination angle between rotation and magnetic axis. We have found that the main parameter that determines the process responsible for gamma-ray photon emission in gap region is spark width (h_\perp). For narrower sparks (higher shielding factor) acceleration potential drop is lower, which results in smaller Lorentz factors of primary particles ($\gamma \sim 10^3 - 10^4$). In this regime the gap will be dominated by ICS. Wider sparks (smaller shielding factor) corresponds to higher acceleration ($\gamma \sim 10^5 - 10^6$) and results in gap dominated by CR. In this case the particles will be accelerated to higher energies before they would upscatter x-ray photons emitted from the hot polar cap. As the determination of spark width is not possible by only using X-ray data we decided to use radio observations to put more strict constraints on PSG model.

3. The drift model

The existence of IAR in general causes rotation of plasma relative to the NS. The power spectrum of radio emission must have a feature due to this plasma rotation. This feature is indeed observed and it is called drifting sub-pulse phenomenon. Using assumption that the spark width and distance between sparks are of the same order, we can define the drifting velocity as

$$v_{dr} = 2h_\perp / (PP_3) \quad (3)$$

where P_3 is the period at which a pattern of pulses crosses the pulse window (in units of pulsar period). In our model drift is caused by lack of charge in IAR, then knowing that $\mathbf{v}_\perp = c\Delta\mathbf{E} \times \mathbf{B}/B^2$ we can use calculation of circulation of electric field to find the dependence of drift velocity on shielding factor

$$v_{dr} = 4\pi\eta h_\perp \cos \alpha / P \quad (4)$$

Finally we can find dependence of shielding factor on observed drift parameters

$$\eta = 1/2\pi P_3 \cos \alpha \quad (5)$$

Knowing that heating luminosity $L_{heat} = \eta n_{GJ} (\Delta V e) c \pi R_{pc}^2$ we can use Eqs. 2 and 5 to find the dependence of heating efficiency ($\xi = L_{heat}/L_{sd}$) on sub-pulse drift parameters

$$\xi \approx 0.15 \left(P_2^\circ / (P_3 W_{\beta 0}) \right)^2, \quad (6)$$

where $W_{\beta 0}$ is the pulse width in degrees calculated with an assumption that impact angle is zero ($\beta = 0$). Thus, radio data allow not only to determine shielding factor (and hence width of the sparks, see Eq. 2) but also observations of sub-pulse drift allow to predict polar cap x-ray luminosity. Tab. 1 presents observed and derived parameters of PSG for pulsars with available radio and x-ray data. Please note that we consider only pulsars with visible hot spot component (old NS). Despite the fact that sample is very small we still managed to determine that for observed pulsars ICS is responsible for gamma-photon generation in IAR.

Table 1. Observed and derived parameters of PSG for pulsars with available radio observations of sub-pulse drift (P_2° , P_3) and X-ray observations of actual polar cap (hot spot). T_s , R_{pc} and B_s was chosen to fit 1σ uncertainty. Please note that for calculations \tilde{P}_2° was used as the predicted value of sub-pulse separation (the observed value is greater than pulse width and can not be interpreted as the actual sub-pulse separation).

Name	P_3 (P)	η	\tilde{P}_2° (deg)	$\log \xi$ (radio)	$\log \xi_{bol}$ (x - ray)	T_s (10^6 K)	B_s (10^{14} G)	R_{pc} (m)	h_\perp (m)
B0628-28	7.0	0.07	7.6	-4.0	-3.6	2.5	2.0	23	3.9
B0834+06	2.2	0.15	1.1	-3.6	-3.3	3.0	2.4	20	1.8
B0943+10	1.8	0.09	8.9	-3.2	-3.3	3.2	2.5	17	2.0
B0950+08	6.5	0.09	2.8	-5.1	-4.5	2.6	2.1	14	0.7
B1133+16	3.0	0.09	2.7	-3.3	-3.1	3.4	2.7	17	2.9
B1929+10	9.8	0.02	5.2	-5.1	-4.2	4.2	2.0	22	1.6

ICS in strong magnetic fields is very efficient process i.e. particle loses most of its energy during scattering. This is the cause of very high multiplicity, M , (number of secondary particles produced by one primary particle). The number density of secondary plasma in PSG model can be described as $n_{sec} = \eta n_{GJ} M$. ICS dominated gap produces two populations of secondary plasma. The first population (higher Lorentz factors) is produced when primary particles lose most of their energy in ICS process. The second population corresponds to particles produced by gamma-ray photons above the gap (lower Lorentz factors).

4. Conclusions

To follow both theoretical predictions and observational data PSG model was proposed. Recent studies on the model showed that cascade scenario in a gap (CR or ICS) strongly depends on spark width. X-ray observations in combination with sub-pulse drift analysis allowed to determine that for observed pulsars ICS is responsible for gamma-ray photon generation in a gap. The exact density of secondary plasma can be calculated only by performing full cascade simulation with inclusion of heating by backstreaming particles. Nevertheless we can still find dependence of multiplicity factor on number of photons upscatterd by one primary particle. We were able to find two populations of secondary plasma with different energy distribution. It turns out that ICS dominated gap creates conditions suitable for generation of radio emission at altitudes several tens of stellar radii.

References

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